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WIND FORCE MEASUREMENT ON A MODEL FUELLING MACHINE TROLLEY IN A SIMULATED LOCA

Report No 89-201-K

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ABSTRACT

An experimental project was undertaken to measure the axial component of wind force on a 1/40th scale model of a Bruce NGS fuelling machine trolley. Force measurements were made with one and two trolleys parked under a non-accident reactor vault and upstream Mach numbers of up to 0.15 and 0.175 were obtained for these two configurations respectively. Pressure loss across the trolley(s) was also measured.

It was found that the drag force coefficient increased rapidly with the Mach number upstream of the trolley(s) and that the pressure loss coefficient agreed well with those obtained in a previous test series.

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**ontario hydro
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TROLLEY IN A SIMULATED LOCA**

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This report describes a series of tests to measure the drag force on a fuelling machine trolley model during a simulated loss of coolant accident in a multi-unit nuclear power station using an air blowdown facility. The test facility consists of 1/40th scale model of a Bruce NGS reactor vault, part of the fuelling machine duct and two fuelling machine trolleys.

In Bruce NGS, the fuelling machine trolleys are immobilized by a locking mechanism when the fuelling machine is servicing a reactor. This locking mechanism was designed based on early handbook estimates of drag forces from flow toward the vacuum building. Analysis based on results in reference/1/ indicated that these forces may be larger than estimated. In order to provide a more realistic estimate, a direct measurement of axial force on a model trolley was recommended.

With these objectives in mind, tests were performed with one and two trolleys parked under a non-accident reactor vault. Accidents were simulated by discharging high pressure air from two large holding tanks through the tunnel. To simulate prototype accident conditions, local Mach numbers of up to 0.175 and 0.15 were obtained for the one and two trolley cases respectively. It was found that the drag force coefficient increased rapidly with the Mach number defined upstream of the trolley(s) in both cases.

for

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To: Mr. W.J. Simmons
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WIND FORCE MEASUREMENTS ON A MODEL FUELLING MACHINE
TROLLEY IN A SIMULATED LOCA

1.0 INTRODUCTION

The CANDU containment system associated with multi-unit stations such as Bruce NGS A and B and Darlington NGS, feature a fuelling duct which interconnects the four reactor vaults to a centrally located vacuum building. Under normal operations, the reactor vaults and the fuelling duct are isolated from the vacuum building by pressure relief valves. In the event of a loss of coolant accident (LOCA), the containment system is pressurized by the high-enthalpy liquid discharge. The resulting increase in pressure, acting across the pressure relief valve pistons, automatically opens the valves and releases the air-steam mixture into the vacuum building. This creates a strong flow in the fuelling duct and consequently a high wind load on fuelling machine trolleys during the transient.

Trolley locks are therefore used to immobilize the fuelling machine when the machine is in service. The locking mechanism was designed in accordance with early handbook estimates of forces for Bruce NGS. Based on recent analyses for Darlington NGS, it appears that the drag forces on a trolley during a transient may be larger than estimated. A review of the original design work is therefore necessary. In order to avoid unnecessarily conservative assumptions in the new design, it is important that drag forces on the trolley be calculated more accurately. Direct drag force measurements using a model trolley are needed to provide the data base for extrapolation to prototype.

The air blowdown test facility in Ontario Hydro Research Division was used to perform the required measurements in simulated LOCAs. Horizontal drag forces on a model trolley were measured, using a load cell, for a range of Reynolds numbers. Details of the experiments and results obtained are described below.

2.0 OBJECTIVES

The objectives of the experiments were as follows:

1. To repeat the pressure drop measurements as in the previous test series/2/ to establish consistency between the two series.
2. To measure the axial wind force on a model fuelling machine trolley for approximately the same range of Mach numbers ($0.1 < Ma < 0.2$) as obtained in the previous test series with one or two trolleys parked under a non-accident reactor, previously termed the tunnel series.

3.0 EXPERIMENTAL FACILITY

3.1 Experimental Setup

The experimental setup is shown schematically in Figure 1. Major components of the test facility are shown in Figures 2 and 3. The same setup was used, in a previous study, to measure the loss coefficient in the fuelling duct with one, two, or no trolleys in the duct/2/. The experiment was designed to model the flow conditions in a Bruce NGS fuelling duct in the event of a LOCA. It was assumed that pressure losses in the flow over the trolleys were predominately due to compressible flow form drag and to a lesser extent frictional losses. Operating conditions in the model were thus obtained by equating the Mach number and the loss coefficient for the model (subscript m) and the prototype (subscript p) respectively:

$$Ma_m = Ma_p \quad (1)$$

$$\frac{\Delta P_m}{1/2 \rho_m V_m^2} = \frac{\Delta P_p}{1/2 \rho_p V_p^2} \quad (2)$$

An appropriate scaling factor was selected by satisfying the condition:

$$Re_m > 2 \times 10^5 \quad (3)$$

where Re is the Reynolds number. It was expected that with equation (3) satisfied, loss coefficients would be independent of Reynolds number for flow over blunt bodies. Physically, it was desirable to have Re_m as close to Re_p as possible. However, the upper limit was governed by

the total mass of air available in the air supply system. A scale of 1/40 th was obtained when all of the constraints were taken into account. Details of the scaling considerations are given in /2/.

3.1.1 Air Supply System

The air handling part of the facility consists of high and medium pressure holding tanks, control valves, piping and various measuring instruments. Flow through the model is attained by discharging the pressurized air from the holding tanks through the duct. The flow is controlled by pneumatically operated control valves, and can be varied by changing the set point of the controller or the initial tank pressure. There are two main holding tanks, connected in series, with a total volume of 4 m^3 and a pressure rating of 5.5 MPa. Downstream of the main tanks is a secondary holding tank with a volume of 0.5 m^3 and a pressure rating of 0.7 MPa. The pressure in the secondary tank is maintained by a control valve downstream of the primary tanks. A second control valve, between the secondary tank and the duct, controls the pressure at the duct inlet. The flow rate is controlled by maintaining a given pressure drop between the secondary tank and the duct. The pressure drop required for a given Mach number was determined by experimentation during commissioning.

3.1.2 Fuelling Duct Model

The model includes a reactor vault, part of the fuelling duct and two fuelling machine trolleys. A cross section of the model is shown in Figure 4. Attention was paid to modeling the system components in detail, especially the trolleys, rails and rail supports. It was sized (1/40 th scale) to simulate the Bruce NGS fuelling duct. Since the Darlington NGS duct is slightly larger, the drag forces measured are expected to be somewhat conservative when applied to Darlington.

In order to measure the wind force on a trolley, it is necessary to reduce friction forces between the trolley and its rails using anti-friction bearings. Two sets of two bearings each were embedded on the top of the model and four sets of four bearings each were set into the rails as shown in Figures 5 and 6 respectively. The bearings in the rails were located such that the model rested on them, ensuring a low friction motion between the model and the rails. The bearings on the top of the model guided against binding on the duct roof if the trolley were to lift off the rails.

One trolley was fitted with anti-friction bearings while the second was bolted in place as force measurements were required on only one trolley (ie, by symmetry, the loads on the trolleys are expected to be equal for practical purposes).

3.2 INSTRUMENTATION

The measured parameters were flow rate, temperature, pressure and wind force. The flow rate was measured using a flow meter in the discharge pipe downstream of the model (Figure 1). The meter was a 200 mm (8inch) DIN design insert venturi tube with a fiberglass body and a bronze throat. Temperatures were measured at various positions along the duct by type K thermocouples and pressures were determined using pressure transducers and pitot-static tubes. Two banks of pitot tubes were used, one located upstream and the other downstream of the trolley model (Figure 1). There were five pitot tubes in each bank and they were arranged in the duct as shown in Figure 7. In the previous test series a similar arrangement was used but with nine pitot tubes. The arithmetic mean of the nine pitot tubes did not vary from any single reading by more than 2 % hence the number of pitot tubes was reduced to five to simplify data collection.

The wind force was measured using a load tension link connected to the trolley by a thin wire cable. The load transducer was kept outside of the duct because of its large size. As can be seen in Figure 8, the wire cable was connected to the load cell from the trolley around a sheave. This sheave was 3.5 mm thick and was mounted on anti-friction ball bearings to ensure low friction. Figure 8 also shows the wire connection and pulley with the duct roof removed and the front end of the trolley (the flow is from the pulley towards the trolley). Another wire cable connected the trolley to the end of the rails and was used to fix the initial position of the trolley. This was done by applying a slight pre-load of about 18 N (4.0 lbf) to the load cell via the spring shown in Figure 9.

The load cell was traceable to National Bureau of Standards (NBS) and was calibrated in-situ to check the accuracy of the entire measurement system. The friction force of the trolley over the bearings was measured during calibration. This was done by connecting a spring scale to the trolley back end and pulling against the load cell. The friction force was obtained as the difference in the force read on the scale and that read on the load cell. It was found that the two readings agreed well within the readability of the hand scale which was 2.2 N (1/2 lbf).

The load cell is shown in Figure 10. It was connected between two pins at 90 degrees to each other. This arrangement ensured an accurate measurement of the force because no bending moments were transmitted to the load cell.

The outputs from the pitot tubes and the flow nozzle were recorded in a micro-computer through a pressure scanner and those from the thermocouples, force gauge and pressure transducers were recorded on a strip chart recorder and, in some tests, on magnetic tape. The magnetic tape was used only as a back-up. The instrumentation, except the computer, is shown in Figure 11.

3.3 Test Matrix

A total of 15 tests were performed including two commissioning tests with no data collection (tests 1 and 2). Four tests were performed for the one trolley case and nine for the two trolley case. The range of Mach numbers covered was about the same as in the first series of tests/2/. They were 0.09 to 0.15 for the two trolley case and 0.11 to 0.175 for the one trolley case.

4.0 EXPERIMENTAL PROCEDURE

The main holding tanks were pressurized by the compressor prior to each test. The time required to obtain 5.5 MPa was about 4 hours. The blowdown was initiated by opening the isolation valve between the secondary holding tank and the duct and by setting the first control valve set point to the desired value. The optimum settings required for a given Mach number were determined by trial runs.

All instruments were switched on and checked for proper operation before each test. Recording was started shortly before blowdown initiation to obtain zero references and to synchronize the chart recorder and the computer output. After between 30 to 60 seconds of quasi-steady state flow, the test was terminated by closing the first control valve. The pressure in the main holding tanks had generally depleted to about 0.7 MPa at the end of each test.

5.0 EXPERIMENTAL RESULTS

5.1 Test data

Test data were recorded in the form of analog voltages on a strip chart and pressure readings from the pressure scanner. The strip chart contained transient responses of temperature, force and holding tank pressure while data sets from the pressure scanner were stored on micro-computer. Figures 12 and 13 show typical (filtered) outputs from the strip chart recorder for test runs 11 and 12 respectively and the corresponding pressure data can be found in Appendix A. As can be seen from these Figures, changes in tank pressure, duct temperatures and trolley force corresponded very well with each other throughout the transients. This was true for all test runs. It is interesting to note that the duct air temperature decayed with time and could drop to as low as -29 C (-20 F).

For data analysis the analog data was read off the charts at selected times with corresponding pressure scanner outputs. Only points which fell in the quasi-static flow region of the test were chosen. Since the pressure scanner data transfer rate to the micro-computer was approximately 4 seconds per scan, between 6 to 10 scans could be taken during the quasi- steady flow for the high flow rate tests. Although each data transfer took about 4 seconds, the actual scan time was only a few milliseconds. This gave a snapshot of the flow at that instant in time.

5.2 Data Reduction

The experimental data were reduced and analyzed based on the following measured quantities.

P_{su} = static pressure upstream of model trolley

P_{sd} = static pressure downstream of model trolley

P_{sn} = static pressure at nozzle

P_{TN} = total pressure at nozzle inlet

P_{th} = nozzle throat static pressure

T_u = absolute temperature upstream of trolley

T_d = absolute temperature downstream of trolley

T_n = absolute temperature at nozzle

F = wind force on model trolley

The following are the equations used in data reduction. A sample calculation can be found in Appendix B.

1. Upstream Density

$$\rho_u = \frac{P_{su}}{T_u R}$$

where R is the gas constant for air

2. Downstream Density

$$\rho_d = \frac{P_{sd}}{T_d R}$$

3. Mass flow through nozzle

3.1 Nozzle pressure ratio

$$PR = \frac{P_{TN}}{P_{th}}$$

3.2 Throat Mach Number

$$M_{th} = \sqrt{\frac{2}{k-1} \left(\left(\frac{k-1}{k} \right) ((PR)^{\frac{k-1}{k}}) - 1 \right)}$$

3.3 Mass flow

$$m = \sqrt{\frac{K}{R T}} (A_{th})(P_{th}) \times \frac{M_{th}}{(1+0.2 M_{th}^2)^3}$$

4. Velocity Upstream

$$V_u = \frac{m}{A_d \rho_u}$$

where A_d is the cross section area of duct

5. Downstream Velocity

$$V_d = \frac{m}{A_d \rho_d}$$

6. Total Pressure Upstream

$$P_{tu} = P_{su} + 1/2(\rho_u V_u^2)$$

7. Total pressure downstream

$$P_{td} = P_{sd} + 1/2(\rho_d V_d^2)$$

8. Dynamic pressure upstream

$$P_{du} = 1/2(\rho_u V_u^2)$$

9. Loss Coefficient

$$C_l = \frac{P_{tu} - P_{td}}{P_{du}}$$

10. Mach Number (Based on Upstream conditions)

$$Ma = \frac{V_u}{\sqrt{(k R T_u)}}$$

11. Reynolds Number (based on upstream conditions)

$$Re = \frac{V_u D_H \rho_u}{\mu}$$

where D_H and μ are the hydraulic diameter of the duct and air viscosity respectively

12. Force Coefficient

$$\phi = \frac{F}{2 P_{tu} A_d}$$

6.0 RESULTS AND DISCUSSION

The data from each test was analyzed using the above equations. The results are summarized in Appendix C.

6.1 Loss Coefficient

The loss coefficient, C_l was plotted against Mach number (Ma) and Reynolds number (Re) for both the one and two trolley cases and is shown in Figures 14 and 15 respectively. As can be seen in the figures, the loss coefficient is almost constant over the range of Mach and Reynolds numbers obtained for both cases. For the two trolley case, results from two tests were found to have a lower loss coefficient than the others. These tests were performed with the valve in the discharge line half open resulting in a higher pressure in the duct. All other tests were performed with the valve at least 3/4 open. The reason for this discrepancy is not clear.

The results were compared directly with those obtained in Reference/2/ and are reproduced in Figures 16 and 17. The following observations can be made:

1. Results from the two test series compared reasonably well.
2. The loss coefficient in the previous test series tended to have wider scatter.
3. In the previous test series, the loss coefficient appeared to increase with Reynolds or Mach numbers for the two trolley case whereas in the present test series it was almost constant.
4. Loss coefficients obtained in the present test series were in general 10% to 20% higher than in the previous test series. The difference may be attributed to the fact that, in the previous test series temperatures were measured only at two locations: upstream of the trolley model and at the flow nozzle. The flow across the model was assumed to be isothermal. Since the temperature along the fuelling duct was dropping as the air expanded, this assumption meant that a higher temperature was used in the calculations for loss coefficient in the previous test series. This resulted in lower loss coefficient as the loss coefficient is related to the inverse of the temperature squared. In the present test series, the temperature downstream of the trolleys was also measured. This provided more accurate temperature data and consequently better loss coefficient estimations.

6.2 Drag Force Coefficient

The drag force coefficient was plotted as a function of the upstream Mach number in Figure 18. Because of a reduction in flow area at the trolley(s), the local Mach number could be significantly higher. This is especially true for the two trolley case. Since the local flow velocity was higher for the two trolley case for the same upstream Mach number, the drag force coefficient was also higher as shown in Figure 18.

It can be seen that the drag force coefficient increases rapidly with Mach number for both cases and the results can be expressed as power functions of the Mach number. The functions are given and are represented by the solid lines in Figure 18.

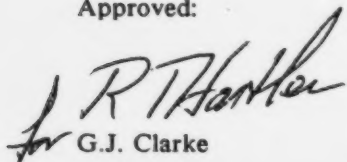
7.0 CONCLUSIONS

1. The data from the present series of tests are consistent with those reported previously/2/. Loss coefficients are approximately constant over the range of Reynolds and Mach numbers achieved for each of the one and two trolley cases.
2. The maximum Mach numbers obtainable using the present test facility are 0.175 and 0.15 for the one and two trolley cases respectively.
3. The axial force coefficient for the fuelling machine trolley during a simulated LOCA was found to be related to Mach number by a power function for both one and two trolley cases.

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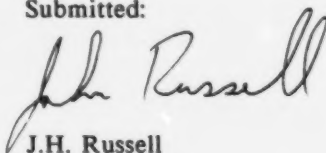
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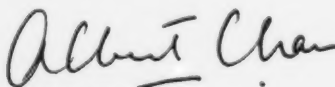
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3. ASME, FLUID METERS THEIR THEORY AND APPLICATION, 6th Edition. The American Society of Mechanical Engineers, 1971.
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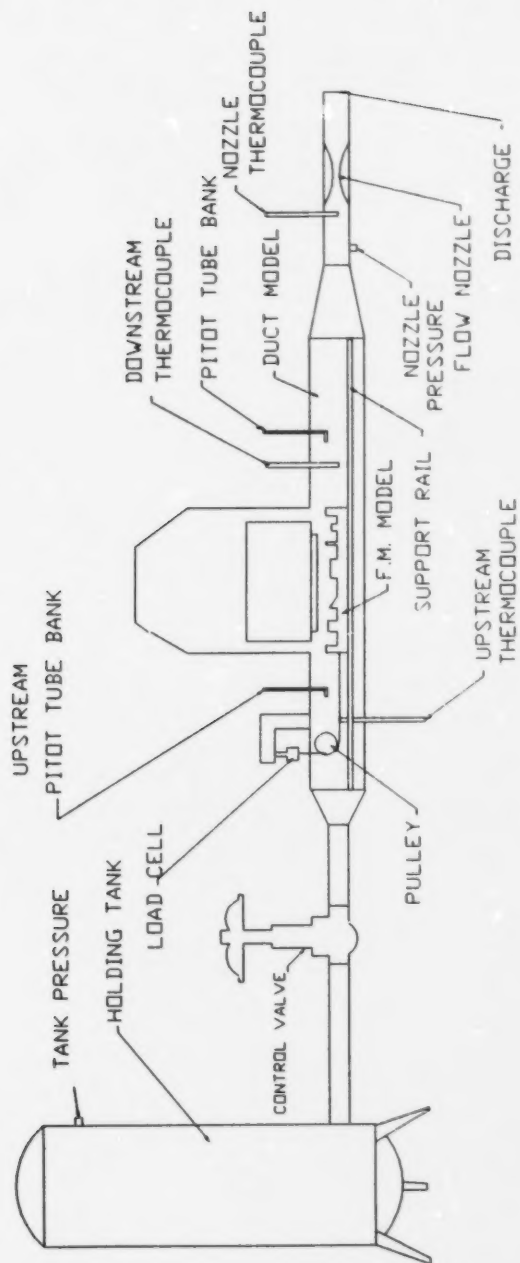


FIGURE 1
FUELING MACHINE DUCT FLOW EXPERIMENTAL SET-UP

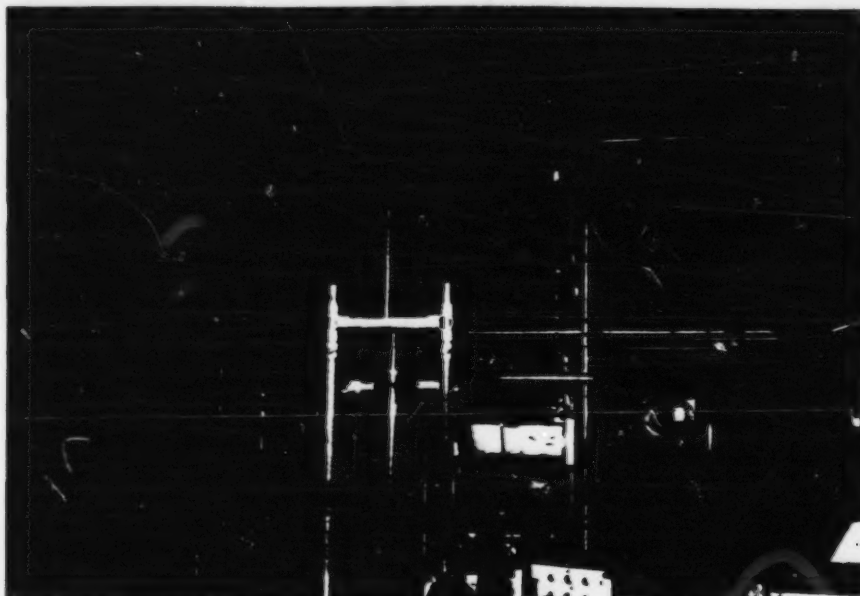


FIGURE 2

OVERALL VIEW OF TEST FACILITY

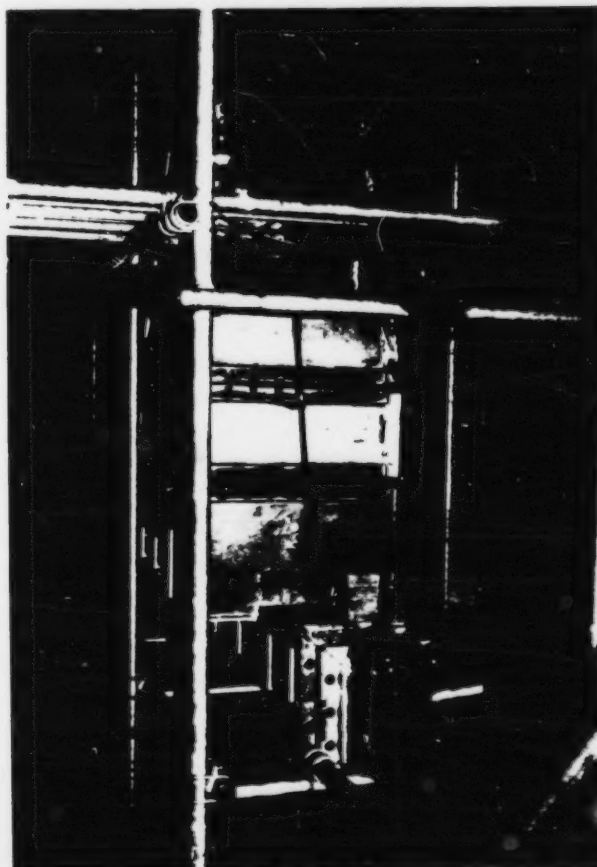


FIGURE 3

FUELING MACHINE DUCT AND REACTOR VAULT MODEL

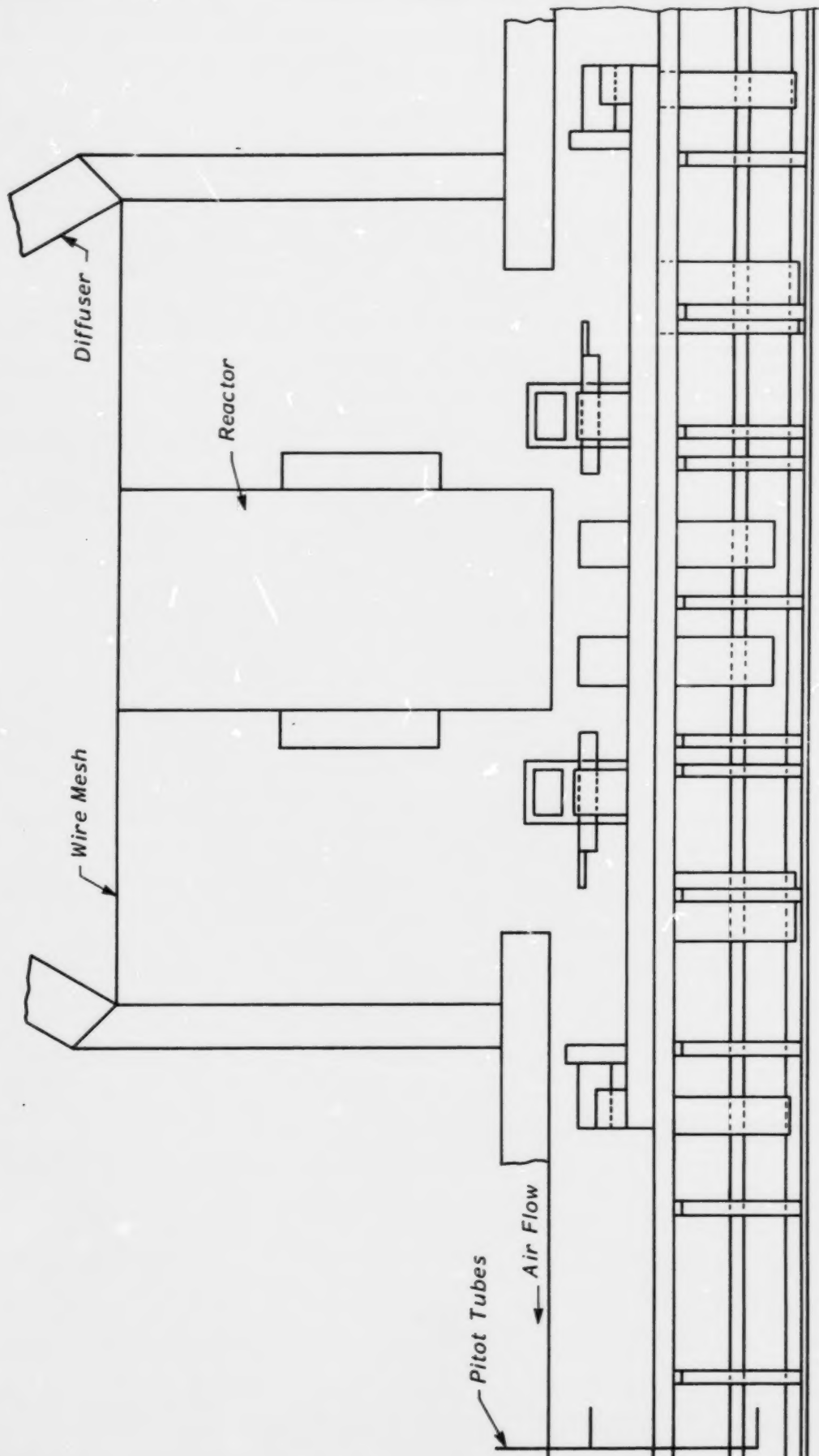


FIGURE 4
CROSS SECTION OF MODEL

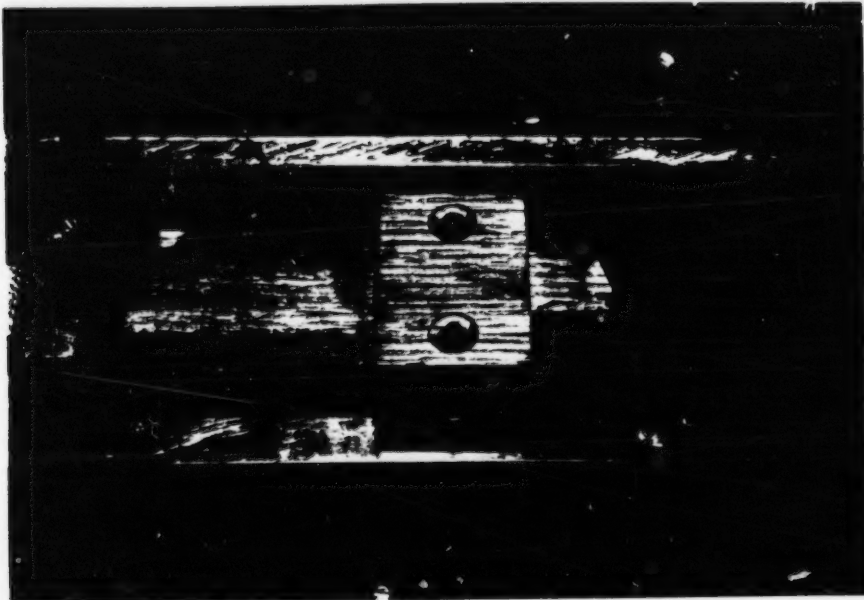


FIGURE 5

BEARINGS EMBEDDED ON TOP OF FUELING MACHINE TROLLEY MODEL



FIGURE 6

BEARINGS SET INTO RAILS

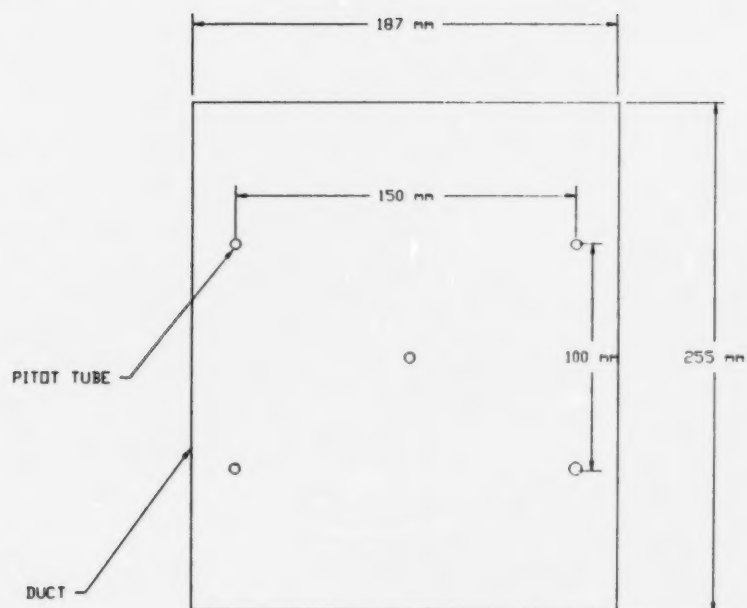


FIGURE 7
PITOT TUBE LAYOUT IN THE DUCT

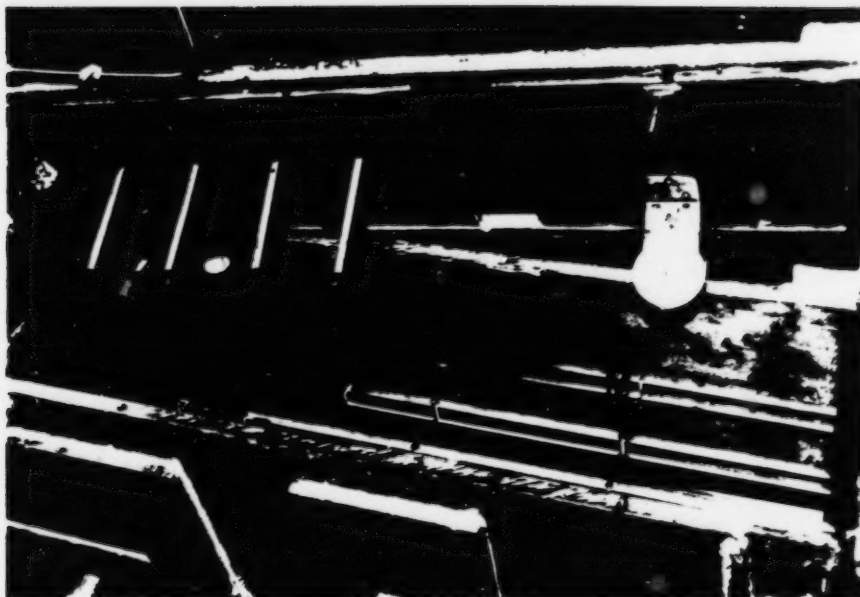


FIGURE 8

LOAD CELL CONNECTION TO FRONT OF TROLLEY

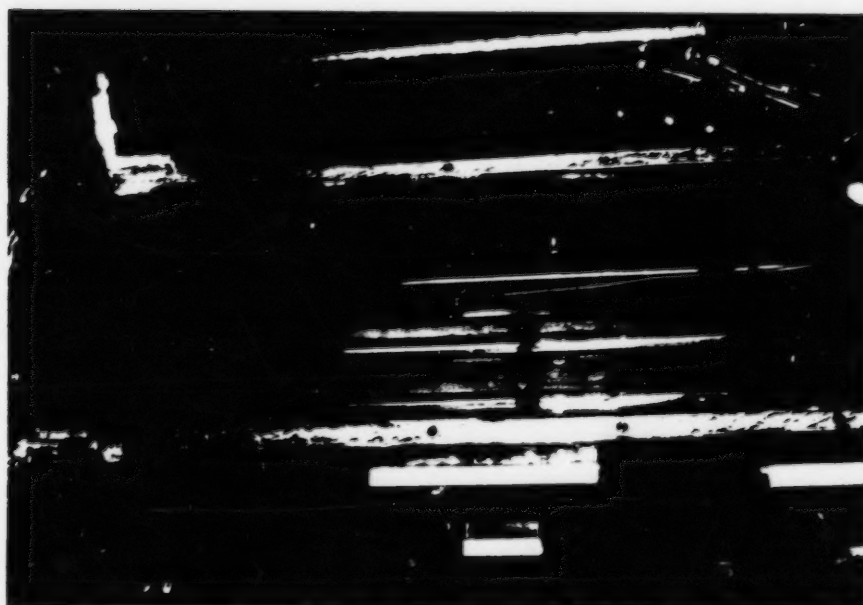


FIGURE 9

DEAD-END CONNECTION OF TROLLEY

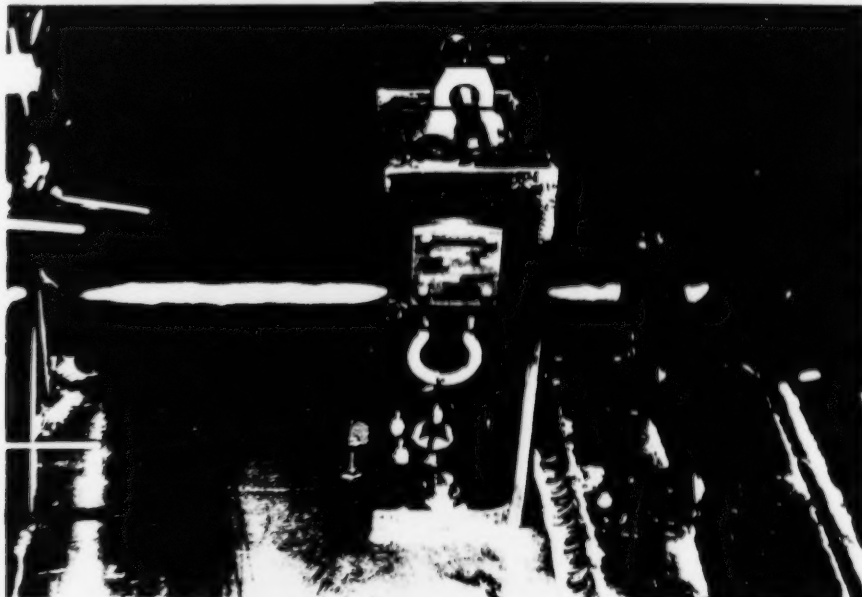


FIGURE 10
LOAD CELL ARRANGEMENT



FIGURE 11
INSTRUMENTATION

TEST 11 - TWO TROLLEYS

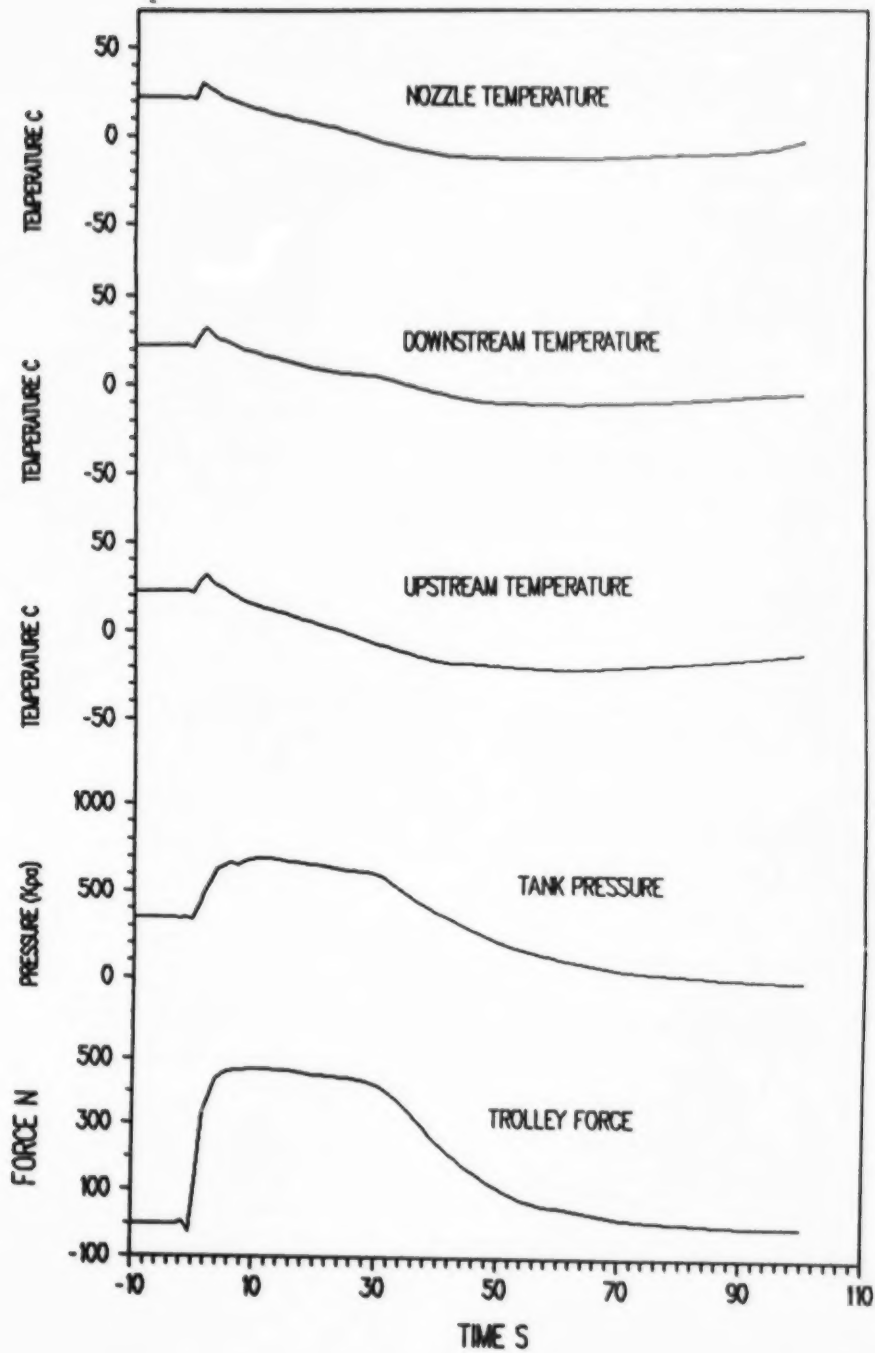


FIGURE 12

TEST 12 - ONE TROLLEY

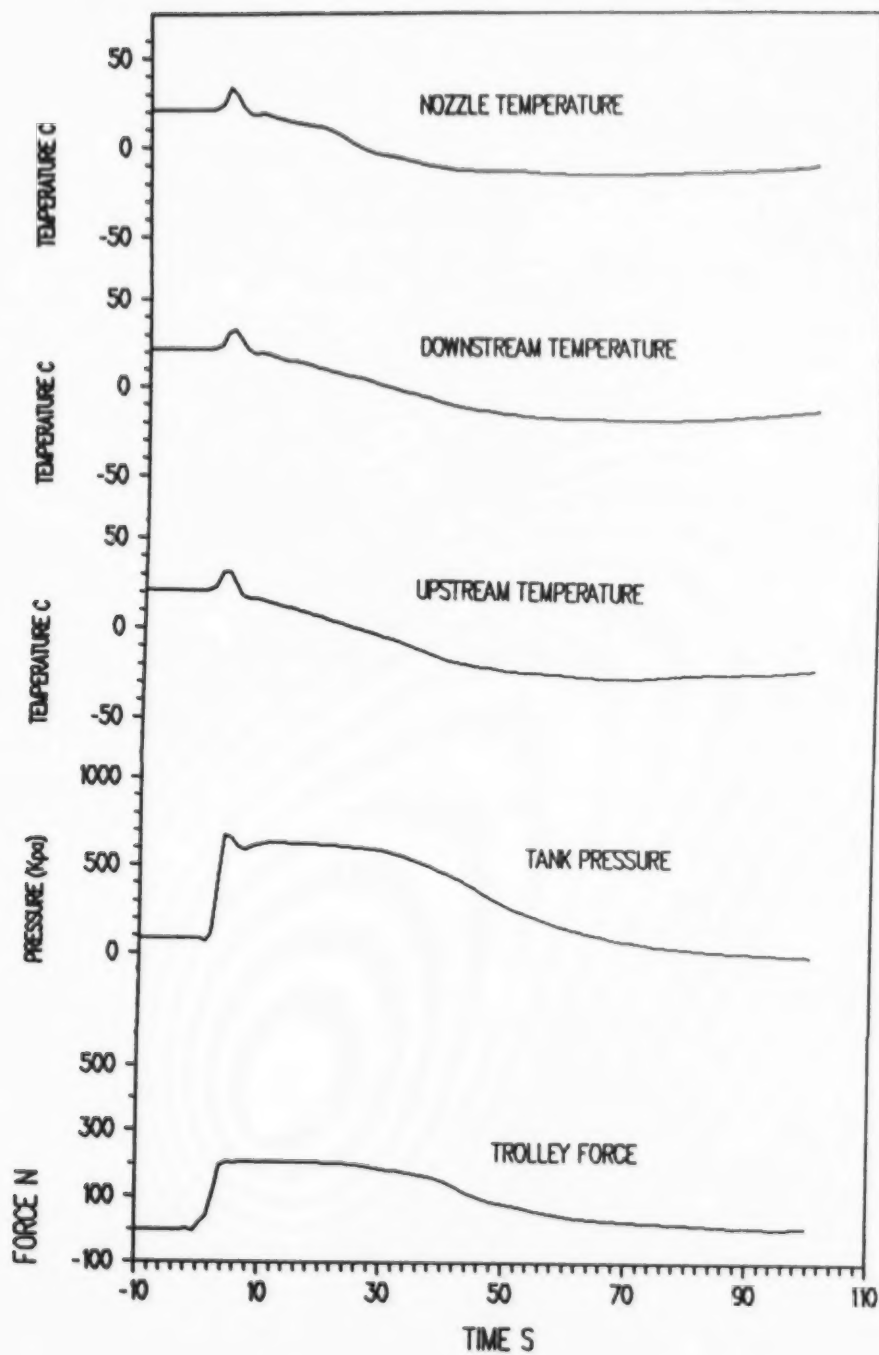


FIGURE 13

LOSS COEFFICIENT VS MACH NUMBER

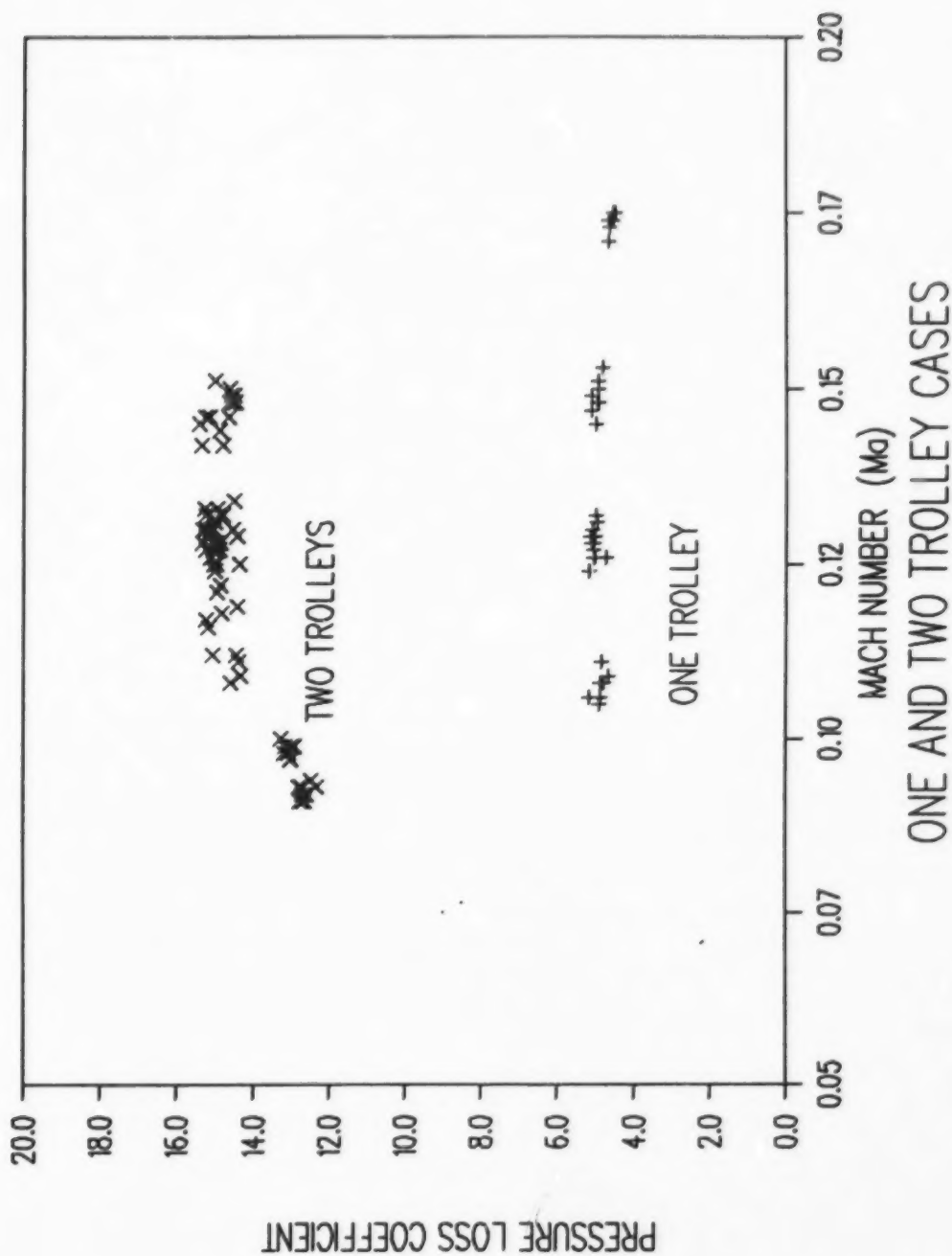


FIGURE 14

LOSS COEFFICIENT VS REYNOLDS NUMBER

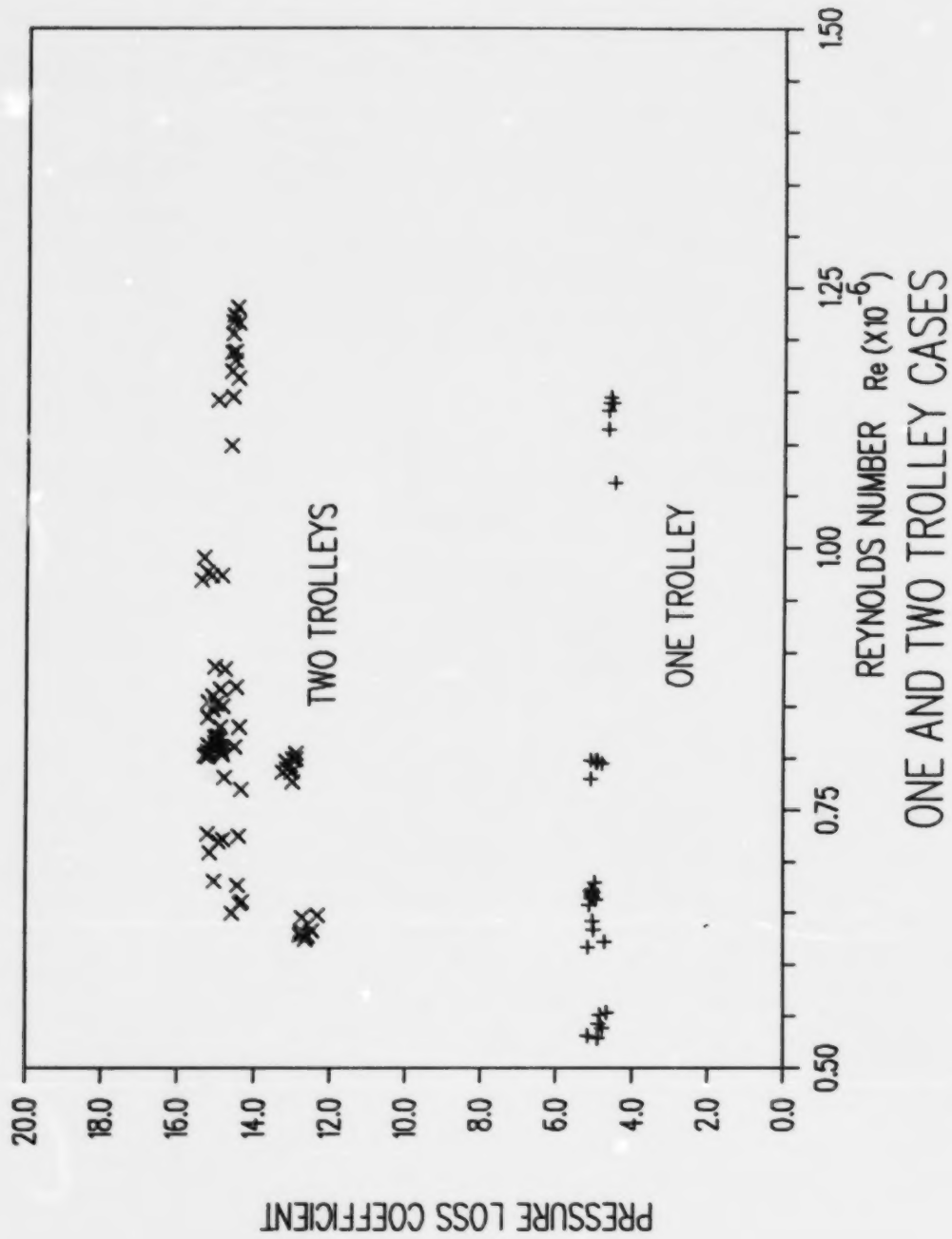


FIGURE 15

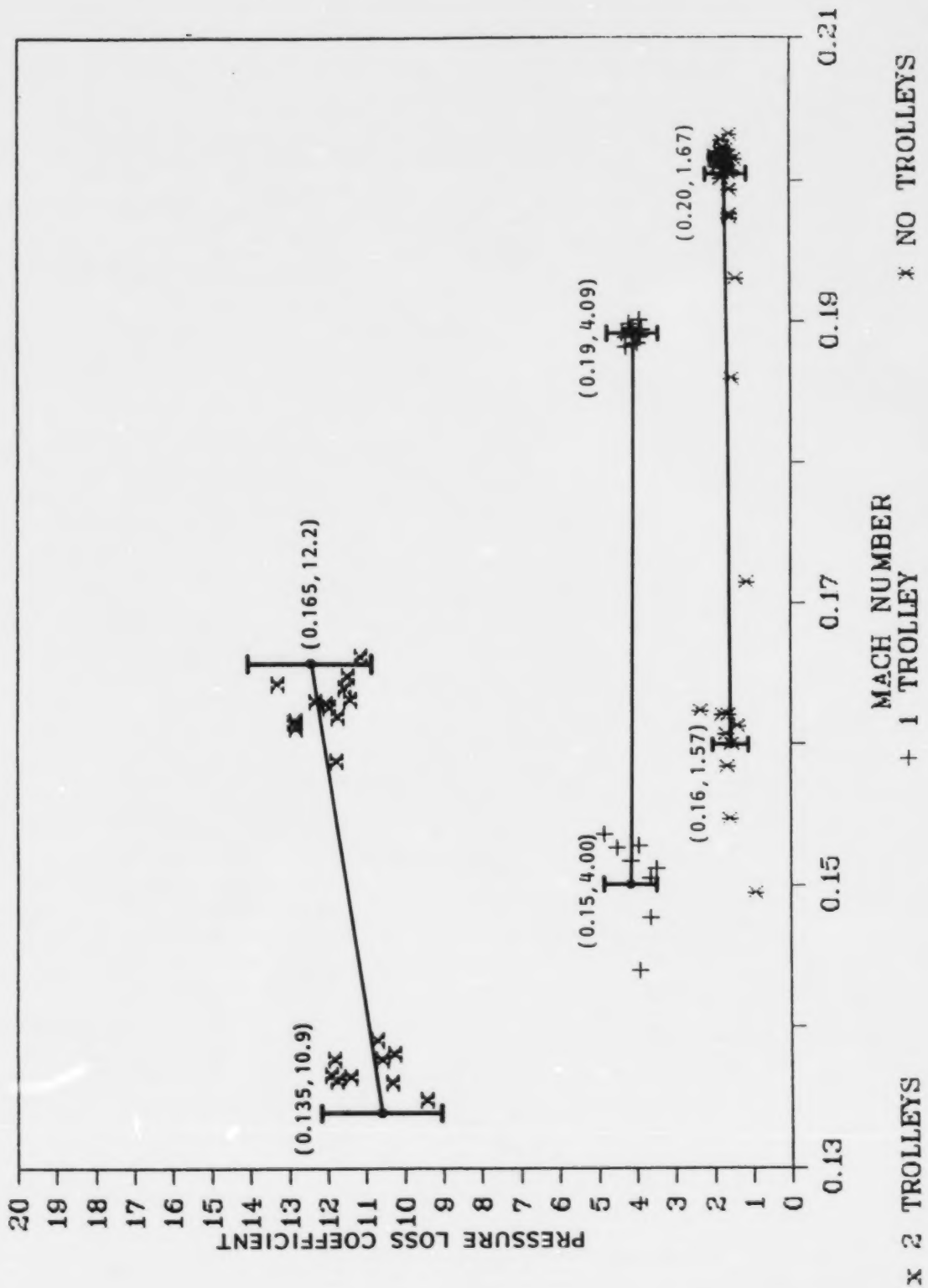


FIGURE 16
FUELLING DUCT OVERPRESSURE
- TUNNEL SERIES
(From Ref [2])

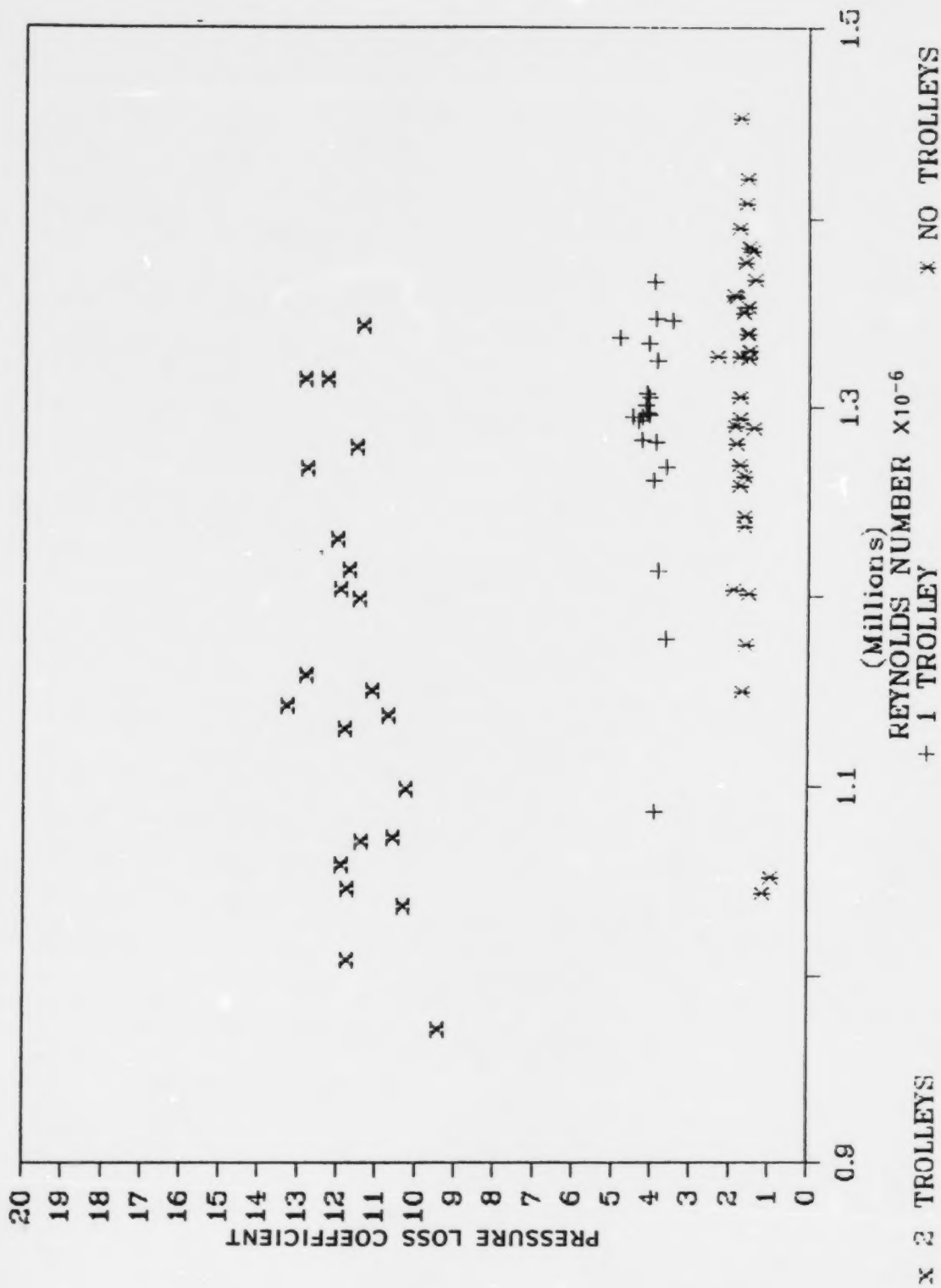
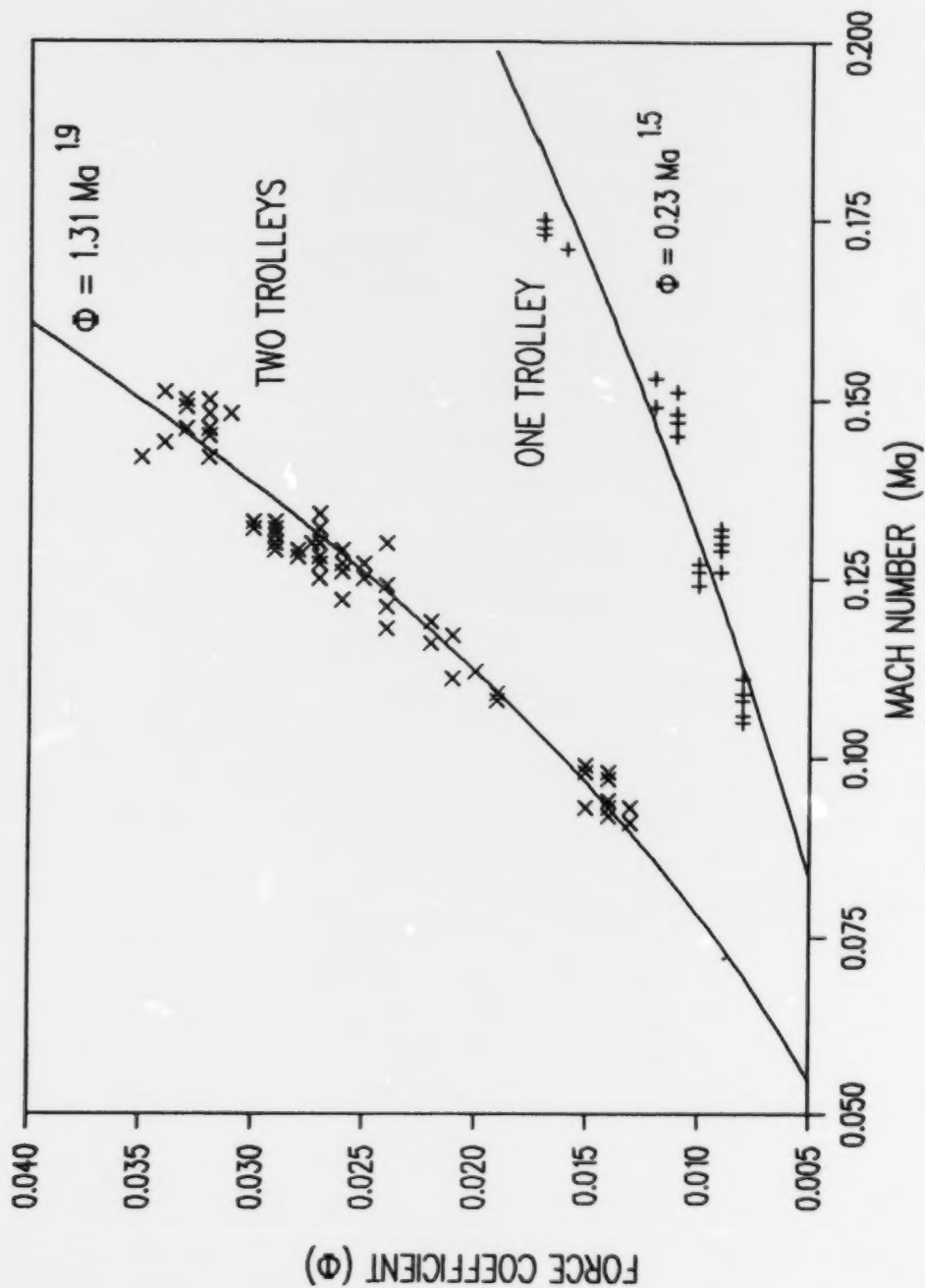


FIGURE 17
LOSS COEFFICIENT VS REYNOLDS NUMBER, TUNNEL SERIES
(From Ref [2])

FORCE COEFFICIENT VS MACH NUMBER



ONE AND TWO TROLLEY CASES

FIGURE 18

APPENDIX A

TABLE A1
COMPUTER OUTPUT FOR TEST 11 (TWO TROLLEYS)

TIME	UPSTREAM		DOWNSTREAM			NOZZLE	
S	STATIC psig	TOTAL psig	STATIC psig	TOTAL psig	TOTAL psig	THROAT psig	STATIC psig
0	0.0112	0.0174	0.0096	0.0068	0.032	0.000	0.000
4	0.0112	0.0208	0.0096	0.0034	0.032	0.000	0.000
8	0.2716	0.3508	0.0706	0.0980	0.175	-0.301	0.088
12	7.5652	8.2052	2.2756	3.1640	2.964	-5.569	2.563
16	10.0892	10.6524	4.5182	5.4658	4.446	-4.816	4.030
20	10.6634	11.2102	5.0568	6.0066	4.765	-4.632	4.348
24	10.4242	10.9862	4.8736	5.8142	4.637	-4.699	4.224
28	10.1950	10.7318	4.6736	5.6046	4.494	-4.749	4.101
32	9.6596	10.1878	4.3074	5.2124	4.064	-4.967	3.694
36	9.0502	9.5650	3.8842	4.7526	3.618	-5.217	3.234
40	7.5360	7.9506	2.7552	3.5390	2.279	-5.836	1.980
44	5.4336	5.7928	1.3458	2.0280	1.100	-3.478	0.778
48	3.9814	4.2580	0.8544	1.3756	0.701	-2.174	0.495
52	2.9390	3.1532	0.5966	0.9770	0.510	-1.472	0.353
56	2.1570	2.3338	0.4236	0.7098	0.398	-1.003	0.230
60	1.5966	1.7384	0.3118	0.5140	0.271	-0.719	0.159
64	1.1882	1.3012	0.2302	0.3822	0.207	-0.518	0.106
68	0.8816	0.9708	0.1692	0.2874	0.159	-0.385	0.088
72	0.6560	0.7228	0.1250	0.2130	0.127	-0.284	0.053
76	0.4870	0.5300	0.0978	0.1556	0.112	-0.201	0.035
80	0.3568	0.3994	0.0740	0.1184	0.080	-0.151	0.018
84	0.2650	0.2928	0.0572	0.0878	0.080	-0.100	0.018
88	0.2016	0.2170	0.0468	0.0678	0.064	-0.067	0.018
92	0.1452	0.1620	0.0400	0.0474	0.048	-0.050	0.018
96	0.1064	0.1238	0.0298	0.0372	0.048	-0.033	0.018
100	0.0818	0.0964	0.0264	0.0336	0.048	-0.017	0.018
104	0.0112	0.0208	0.0096	0.0034	0.032	-0.000	0.000

TABLE A2

COMPUTER OUTPUT FOR TEST 12 (ONE TROLLEY)

TIME	UPSTREAM		DOWNSTREAM			NOZZLE	
S	STATIC psig	TOTAL psig	STATIC psig	TOTAL psig	TOTAL psig	THROAT psig	STATIC psig
0	0.0148	0.0242	0.0132	0.0102	0.032	0.000	0.000
4	0.0254	0.0380	0.0232	0.0134	0.032	0.000	0.000
8	3.6364	4.3628	1.8454	2.3822	3.586	-5.318	3.040
12	5.0170	5.7604	3.1626	3.8406	3.124	-5.518	2.687
16	5.9044	6.6448	3.9154	4.6648	3.809	-5.167	3.341
20	6.0276	6.8172	4.0542	4.8000	4.064	-5.050	3.553
24	5.8094	6.5660	3.8746	4.5874	3.777	-5.201	3.217
28	5.6122	6.3318	3.6882	4.3914	3.522	-5.301	3.022
32	5.3200	6.0530	3.4270	4.1174	3.347	-5.435	2.775
36	4.9858	5.6816	3.1526	3.8306	2.805	-5.619	2.474
40	3.9958	4.6320	2.2748	2.8942	1.928	-4.833	1.538
44	2.8970	3.4208	1.3600	1.9048	1.179	-3.478	0.831
48	2.1852	2.5712	0.9428	1.3850	0.861	-2.375	0.530
52	1.6108	1.8964	0.6542	0.9844	0.558	-1.555	0.371
46	1.1884	1.3908	0.4646	0.7146	0.430	-1.087	0.230
60	0.8746	1.0292	0.3490	0.5158	0.303	-0.769	0.159
64	0.6384	0.7712	0.2506	0.3878	0.239	-0.552	0.106
68	0.4695	0.5784	0.1892	0.2832	0.175	-0.401	0.088
72	0.3568	0.4302	0.1418	0.2090	0.143	-0.284	0.071
76	0.2614	0.3166	0.1080	0.1584	0.112	-0.217	0.053
80	0.2016	0.2410	0.0874	0.1182	0.112	-0.151	0.018
84	0.1524	0.1862	0.0640	0.0908	0.080	-0.100	0.018
88	0.1170	0.1412	0.0536	0.0708	0.064	-0.067	0.018
92	0.0818	0.1032	0.0400	0.0508	0.064	-0.050	0.018
96	0.0642	0.0794	0.0332	0.0404	0.048	-0.033	0.000
100	0.0464	0.0658	0.0264	0.0300	0.048	-0.017	0.000
104	0.0430	0.0588	0.0264	0.0236	0.048	-0.017	0.000
108	0.0326	0.0414	0.0232	0.0234	0.048	-0.017	0.000
112	0.0290	0.0346	0.0232	0.0102	0.048	-0.000	0.000

APPENDIX B

SAMPLE CALCULATIONS

The following is a sample calculation for the second set of data taken from test set number 11 (two trolley case)

Parameters Measured

Upstream Conditions

P_{su} static pressure = 170.9 kPa (10.09 psig)
 P_{tu} total pressure = 174.8 kPa (10.65 psig)
 T_u temperature = 10.6°C (51°F)

Downstream Conditions

P_{sd} static pressure = 132.5 kPa (4.52 psig)
 P_{td} total pressure = 139.0 kPa (5.47 psig)
 T_d temperature = 15.0°C (59°F)

Nozzle Conditions

P_{sn} inlet static pressure = 129.1 kPa (4.03 psig)
 P_{tn} inlet total pressure = 132.0 kPa (4.45 psig)
 P_{thn} throat static pressure = 69.4 kPa (-4.63 psig)
 T_n temperature = 14.9°C (57°F)

Force on Trolley $F = 467 \text{ N (105 lbf)}$

Constants Used

R gas constant = 286.7 m.N/Kg.K (53.3 ft.lbf/lbm.°R)
 g gravity = 9.81 m/s² (32.2 ft/s²)
 k specific heat ratio = 1.4
 A_{th} throat area = 0.0140 m²
 A_d duct area = 0.0417 m²
 D_h hydraulic diameter = 0.1991 m

Data Reduction

1. Upstream Density

$$\rho_u = \frac{P_{su}}{T_u R} = \frac{170900}{(10.6 + 273.7) 286.7} = 2.1 \text{ kg/m}^3$$

2. Downstream Density

$$\rho_d = \frac{P_{sd}}{T_d R} = \frac{132500}{(15.0 + 273.2) 286.7} = 1.6 \text{ kg/m}^3$$

3. Mass flow through nozzle

3.1 Nozzle pressure ratio

$$PR = \frac{P_{TN}}{P_{th}} = \frac{132.0}{69.4} = 1.90$$

3.2 Throat Mach Number

$$M_{th} = \sqrt{\frac{2}{k-1} \left(\frac{\frac{k-1}{k}}{(PR)} - 1 \right)} = \sqrt{\frac{2}{0.4} \left(\frac{0.2857}{1.90} - 1 \right)} = 1.01$$

3.3 Mass flow

$$m = \sqrt{\frac{k}{R T}} (A_{th})(P_{th}) \times \frac{M_{th}}{(1+0.2 M_{th}^2)^{3/2}}$$

$$= \sqrt{\frac{1.4}{286.7 \times (14.9 + 273.2)} \times (0.014)(132000) \frac{1.01}{(1 + 0.2(1.01)^2)^3}}$$

$$= 4.40 \text{ kg/s}$$

4. Velocity Upstream

$$V_u = \frac{\dot{m}}{A_d \rho_u} = \frac{4.40}{0.0417 \times 2.1} = 50.3 \text{ m/s}$$

5. Downstream Velocity

$$V_d = \frac{\dot{m}}{A_d \rho_d} = \frac{4.40}{0.0417 \times 1.6} = 65.9 \text{ m/s}$$

6. Total Pressure Upstream

$$\begin{aligned} P_{tu} &= P_{su} + 1/2 \rho_u V_u^2 \\ &= 170900 + 1/2(2.1 (50.3)^2) \\ &= 170900 + 2653 \\ &= 173.6 \text{ kPa} \end{aligned}$$

7. Total pressure downstream

$$\begin{aligned} P_{td} &= P_{sd} + 1/2(\rho_d V_d^2) \\ &= 132500 + 1/2(1.6 (65.9)^2) \\ &= 132500 + 3476 \\ &= 136.0 \text{ kPa} \end{aligned}$$

8. Dynamic pressure upstream

$$\begin{aligned} P_{du} &= 1/2(\rho_u V_u^2) \\ &= 1/2 (1.2 \times (50.2)^2) \\ &= 2.6 \text{ kPa} \end{aligned}$$

9. Loss Coefficient

$$C_l = \frac{P_{tu} - P_{td}}{P_{du}} = \frac{173.6 - 136.05}{2.6} = 14.2$$

10. Mach Number (Based on Upstream conditions)

$$\begin{aligned} Ma &= \frac{V_u}{(k R T_u)} = \frac{50.2}{(1.4 \times 286.7 \times (14.9 + 273.2))} \\ &= 0.15 \end{aligned}$$

11. Reynolds Number (based on upstream conditions)

11.1 Viscosity

$$\begin{aligned} \mu &= 1.71141 + 0.007925 T_u + -0.0000284 T_u^2 \\ &= 1.71141 + 0.007925 \times 10.6 - 0.0000284 \times (10.6)^2 \\ &= 1.79 \times 10^{-5} \text{ kg/m.s} \end{aligned}$$

11.2 Reynolds number

$$\begin{aligned} Re &= \frac{V_u D_H \rho_u}{\mu} = \frac{50.2 \times 0.199 \times 2.1}{0.0000179} \\ &= 1.17 \times 10^6 \end{aligned}$$

12. Force Coefficient

$$\phi = \frac{F}{2 P_{tu} A_d} = \frac{467}{2 (173000) (0.042)} = 0.032$$

APPENDIX C
TABLE C1

SUMMARY OF RESULTS
TWO TROLLEYS

TEST	MACH NUMBER	REYNOLDS NUMBER $\times 10^{-6}$	LOSS COEFFICIENT	FORCE COEFFICIENT
3	0.093	0.629	12.72	.015
	0.094	0.632	12.45	.014
	0.092	0.628	12.80	.014
	0.092	0.629	12.71	.014
	0.092	0.627	12.57	.014
	0.092	0.629	12.60	.013
	0.091	0.624	12.64	.013
	0.091	0.632	12.76	.013
	0.093	0.647	12.33	.013
	0.091	0.645	12.72	.013
4	0.100	0.786	13.25	.016
	0.099	0.798	12.97	.015
	0.099	0.789	13.14	.015
	0.099	0.799	13.00	.015
	0.099	0.798	12.90	.015
	0.099	0.804	12.91	.015
	0.098	0.796	13.18	.015
	0.097	0.785	13.02	.014
	0.098	0.793	13.04	.014
	0.097	0.777	12.99	.014

TABLE C1 (CONTINUED)
SUMMARY OF RESULTS
TWO TROLLEYS

TEST	MACH NUMBER	REYNOLDS NUMBER $\times 10^{-6}$	LOSS COEFFICIENT	FORCE COEFFICIENT
5	0.123	0.780	14.77	.030
	0.133	0.803	15.2	.0294
	0.132	0.801	15.2	.0291
	0.133	0.816	14.9	.0303
	0.130	0.802	15.3	.0292
	0.131	0.811	14.9	.0299
	0.130	0.806	15.2	.0292
	0.128	0.802	15.3	.0281
	0.129	0.812	15.2	.0282
	0.128	0.819	15.0	.0273
6	0.128	0.810	14.9	.0274
	0.128	0.811	14.9	.0276
	0.127	0.807	14.8	.0277
	0.127	0.815	15.0	.0264
	0.129	0.830	14.3	.0269
	0.126	0.809	15.0	.0267
	0.127	0.829	14.9	.0260
	0.125	0.812	15.0	.0251
	0.125	0.821	14.9	.0256
	0.124	0.818	14.9	.0248
7	0.134	0.868	14.4	.0278
	0.129	0.839	15.2	.0292
	0.132	0.866	14.9	.0271
	0.130	0.851	15.0	.0272
	0.130	0.860	15.0	.0279
	0.132	0.887	15.0	.0275

TABLE C1 (CONTINUED)

SUMMARY OF RESULTS
TWO TROLLEYS

TEST	MACH NUMBER	REYNOLDS NUMBER $\times 10^{-6}$	LOSS COEFFICIENT	FORCE COEFFICIENT
7	0.134	0.868	14.48	.027
	0.129	0.839	15.22	.029
	0.132	0.866	14.91	.027
	0.130	0.851	15.02	.027
	0.130	0.860	15.09	.027
	0.132	0.887	15.05	.027
	0.128	0.850	14.84	.027
	0.127	0.854	15.21	.027
	0.126	0.847	15.10	.026
	0.122	0.803	14.84	.026
8	0.125	0.769	14.34	.027
	0.118	0.721	14.80	.024
	0.116	0.708	15.15	.022
	0.117	0.727	15.23	.021
	0.119	0.724	14.41	.022
	0.111	0.659	14.37	.021
	0.112	0.681	15.05	.020
	0.112	0.677	14.43	.020
	0.108	0.649	14.57	.019
	0.109	0.661	14.31	.019
9	0.142	0.885	14.78	.035
	0.145	0.969	15.39	.032
	0.146	0.977	15.24	.032
	0.146	0.973	15.13	.033
	0.130	0.811	14.53	.024
	0.121	0.720	14.92	.024
	0.144	0.973	14.87	.034
	0.142	0.991	15.35	.032

TABLE C1 (CONTINUED)

SUMMARY OF RESULTS
TWO TROLLEYS

TEST	MACH NUMBER	REYNOLDS NUMBER $\times 10^{-6}$	LOSS COEFFICIENT	FORCE COEFFICIENT
10	0.151	1.142	14.98	0.34
	0.150	1.206	14.60	0.32
	0.149	1.224	14.58	0.32
	0.148	1.217	14.61	0.32
	0.149	1.232	14.48	0.33
	0.148	1.216	14.47	0.32
11	0.150	1.146	14.59	.033
	0.148	1.175	14.62	.032
	0.148	1.182	14.56	.031
	0.148	1.188	14.63	.031
	0.148	1.189	14.55	.032
	0.148	1.164	14.47	.031
	0.146	1.099	14.62	.032

TABLE C2
SUMMARY OF RESULTS
SINGLE TROLLEY

TEST	MACH NUMBER	REYNOLDS NUMBER $\times 10^{-6}$	LOSS COEFFICIENT	FORCE COEFFICIENT
12	0.175	1.063	4.48	.017
	0.174	1.114	4.67	.017
	0.175	1.140	4.55	.017
	0.174	1.142	4.46	.017
	0.173	1.141	4.63	.017
	0.174	1.145	4.59	.017
	0.171	1.132	4.66	.016
13	0.153	0.795	4.80	.012
	0.149	0.780	5.11	.012
	0.151	0.798	4.93	.011
	0.150	0.796	4.94	.011
	0.148	0.796	4.97	.011
	0.148	0.797	4.94	.011
	0.147	0.798	5.11	.011
	0.145	0.797	4.99	.011
14	0.126	0.621	4.72	.009
	0.131	0.663	4.96	.009
	0.130	0.664	5.07	.009
	0.129	0.658	5.12	.009
	0.132	0.679	4.98	.009
	0.129	0.670	5.01	.009
	0.128	0.668	5.08	.009
	0.128	0.672	5.10	.009
	0.128	0.673	5.04	.009
	0.126	0.666	5.04	.009

TABLE C2 (CONTINUED)

SUMMARY OF RESULTS
SINGLE TROLLEY

TEST	MACH NUMBER	REYNOLDS NUMBER $\times 10^{-6}$	LOSS COEFFICIENT	FORCE COEFFICIENT
15	0.124	0.616	5.15	.010
	0.126	0.633	5.01	.010
	0.127	0.642	5.05	.010
	0.111	0.551	4.84	.008
	0.106	0.530	5.15	.008
	0.108	0.538	4.77	.008
	0.108	0.541	4.87	.008
	0.105	0.528	4.91	.008
	0.109	0.552	4.65	.008
	0.106	0.543	4.88	.008